CHAPTER 5

IN-SITU ELECTRIC FIELD MEASUREMENTS DURING SPREAD F

5.1 Rocket - Borne Double Probe System

This chapter discusses the first in-situ measurements of electric field fluctuations made during the fully developed spread-F conditions from a low latitude station, SHAR (13° 42' N, 80° 14' E, dip 14° N), India. These observations were made simultaneously with electron density measurements discussed in the previous chapter. The double probe system flown on RH-560 rocket on October 4, 1988 was essentially similar to that discussed by Pal et al. (1983) and Pal (1985). As mentioned earlier, vertical electric field measurements were made by a pair of cylindrical sensors mounted on a boom extended in front of the rocket along its spin axis. The cylindrical shape of the sensors was chosen for following reasons: (a) It has been discussed in Chapter 2 that the reduction in the ion current improves the sensor performance. For a cylindrical sensor mounted concentrically on a thin boom, the ion current can be reduced by insulating it from the top side as the ion current is mainly collected from the front surface of a moving sensor, (b) the projected area of a sphere, in a direction perpendicular to the spin axis, is less than that of a cylinder of diameter and height equal to the diameter of the sphere. Thus the effective area for the collection of electron current is more for a cylindrical sensor. This increase in the
effective area of the sensor results in a reduced sensor impedance which improves the frequency response of the double probe system. The side sensors, which were deployed perpendicular to the spin axis, for the determination of horizontal electric field, could not be made cylindrical for mechanical reasons.

A constant current of about 90 nA was fed to each of the electric field sensors to reduce the sheath resistance. Significance of low sheath resistance has been discussed in Chapter 2. To reduce the contact potential asymmetry on the sensor surface, a uniform coating of aquadag was applied to each sensor.

Fig. 5.1 shows a simplified block diagram of the electric field double probe system. Band pass filters were used to study the small scalesize irregularities. Data were separated into two channels (a) 0-100 Hz for studying large scale structures and (b) 50 - 500 Hz, for studying medium scale structures. The pass band in the latter frequency range corresponded to irregularities with scalesizes in the range of 30 m to 3 m for a rocket moving with a velocity of about 1.5 kms\(^{-1}\). An extra gain of about 30 was given to the signals during filtering process. Vertical electric field fluctuations were measured by a pair of double probe separated by 1 m along the spin axis and electric field perturbations normal to the spin axis were determined by a pair of double probe separated by 2.4 m. If the wavelength of an electrostatic wave is shorter than the separation distance between the electrodes than the full electric field potential \(-E.d\) is not measured (Fejer and Kelley, 1980).

5.2 V x B Induced Field

As mentioned earlier, the V x B induced field arises due to the motion of the double probe system across the geomagnetic field B. An estimation of the magnitude of this term has been made along the spin axis of the rocket and also across it during the course of the rocket flight. If \(\psi\) is the dip angle
Fig. 5.1 Schematic of Electric Field Probe
of the location of the rocket at any instant and \( \varphi' \) is the angle which the velocity vector makes with the geomagnetic North i.e. azimuth of the rocket, then the induced field along the spin axis and perpendicular to it are given by:

\[
\Phi_I = B \sqrt{V_v^2 + V_H^2} \sin(\varphi + \varphi') \cos\left[ \tan^{-1}\left( \frac{V_v}{V_H} \right) \pm \theta \right] \quad (5.2)
\]

\[
\Phi_\perp = B \sqrt{V_v^2 + V_H^2} \sin(\varphi + \varphi') \sin\left[ \tan^{-1}\left( \frac{V_v}{V_H} \right) \pm \theta \right] \quad (5.3)
\]

where \( \theta \) is the angle between the rocket spin axis and the vertical, \( V_v \) and \( V_H \) are the vertical and horizontal components of the rocket velocity respectively, \( B \) is the earth’s magnetic field as shown in the Fig. 5.2. Here the plus sign is applicable during ascent and the minus sign during descent. Fig. 5.3 and 5.4 show the \( V \times B \) component induced across and along the spin axis for different values of the rocket orientation angle \( \theta \). It can be seen from these figures that (a) as \( \theta \) increases, the induced field during ascent and descent also increases and (b) the difference between the \( V \times B \) component during the upleg and the downleg motion of the rocket is more for the component of the induced field across the rocket spin axis as compared to that induced along it.

### 5.3 On Board Data Handling with SDS

As discussed above, the \( V \times B \) induced field in the low latitude equatorial F region is ~ 20 - 40 mV/m depending on the velocity of the rocket and the angle between the spin axis and the vertical. This poses serious problem in the determination of the ionospheric electric fields which are typically 1 mV/m. The slowly varying contact potential of the sensor gives rise to slowly changing potential. To eliminate the dc and slowly changing voltage from the potential difference measured by the axial (A - B) and the side (C - D) sensors, a Suitable DC Subtractor (SDS) system was used, so that the ac fluctuations of smaller amplitude embedded in it can be
Fig. 5.2 Attitude of the rocket during ascent.
Fig. 5.3 Induced Electric field due to $V \times B$ effect across the rocket spin axis for different inclination of spin axis with respect to the vertical.
Fig. 5.4 Electric field induced due to $V \times B$ effect in the direction parallel to the rocket spin axis for various angles between the spin axis and the vertical.
amplified. To achieve the accuracy required for these measurements, extra gain was necessary. The principle of SDS operation is as follows.

The signal is amplified at the input stage in a preamplifier, with a predecided gain and the output is monitored with a window comparator to detect the upper and lower limits of the signal. During the course of the flight, whenever the change in the dc component of input signal becomes large enough to bring the output signal to one extreme end of the telemetry channel, a digital counter either counts up or down. As a result, a predecided voltage step is either subtracted from or added to the input signal, to bring the output within the limits of the telemetry channel. Information about the voltage step is also telemetered to the ground in the form of dc level.

**Determination of Electric Field**

The electric field component parallel to the spin axis (E_v) of the rocket was determined by dividing the potential difference between the axial sensors by the separation between them. As discussed above, the primary function of SDS was to enhance the ac fluctuations superimposed on dc field. Since the dc switchings that are introduced by SDS circuit incorporated in the payload were telemetered to ground, a new data series was generated by adding or subtracting appropriate dc shift to the data. The new series gave the actual potential difference measured between the sensors A and B. The resultant was then divided by the separation between the sensors to obtain the electric field component in the vertical direction. Similarly the potential difference between the side sensors was obtained by adding or subtracting the dc output from the SDS data. This can be understood by the block diagram shown in Fig. 5.5. Here X represent the output of the operational amplifier which gives the potential difference between the sensors (A - B) or (C - D) which is amplified by the gain of preamplifier, N. This is passed through the comparator unit and if it does not lie between 0 and 5 volts which represents the two extremes for the signal,
Fig. 5.5 Schematic of Suitable DC Subtractor.
the counter is triggered. This is followed by the subtraction or addition of the signal by a step constant (which is ~ 1.2 in this case) resulting in the output Y. The whole process can be written in the form of the equation:

\[ G^*(X \times N - Y) = SDN \]  

(5.3)

where \( Y = DCN \times k \), \( k \) being a step constant. thus,

\[ X \times N = \frac{SDN}{G} + DCN \times K \]  

(5.4)

\[ X = \frac{SDN}{(G \times N)} + DCN \times \frac{k}{N} \]  

(5.5)

The values of \( G \) and \( N \) were adjusted by visual inspection of the data to obtain smoothly joined data set. Here \( G \) is the gain of the difference amplifier (~ 20 in this case), \( SDN \) and \( DCN \) represent the two channels telemetered to the ground which were used for retrieval of the potential difference between the sensors.

5.4 Procedure of Analysis of the Electric Field Data

The raw data series obtained by the above methodology exhibited a sinusoidal variation corresponding to the spin rate of the rocket which was approximately 3.5 Hz. This can be seen in the Fig. 5.6. For studying the nature of structures, it was necessary to remove the spin modulation from the data. As mentioned before the inclination of the spin axis of the rocket was approximately 9° from the vertical and was fairly stable in space with a precession angle of about ±10°. Hence, \( E_z \) measured along the spin axis would be very close to the vertical electric field quite well. The \( V \times B \) effect was removed by taking the running average of about 10 seconds of data and then subtracting the smoothened signal from the original data. In order to eliminate the spin modulation for viewing large scale structures (\( \lambda > 400 \) m), a low pass filter (cut off frequency at 3 Hz) was applied. Another alternative method was also used for removal of the spin modulation. In this method a sine wave having same amplitude as the original data and which is \( \pi \) degree out of phase with it was subtracted from the raw data, the effect is shown in Fig. 5.7 (a, b).
Fig. 5.6 Sample of electric field data showing the effect of spin modulation both across and along the spin axis.
Fig. 5.7 (a) Electric field fluctuations superimposed on the sinusoidal wave due to spin effect, (b) Residual data after removing the spin effect by subtracting a sine wave which is 180 degree out of phase with the original series.
$E_{H'}$ which represents the electric field component perpendicular to the spin axis of the rocket is derived from the potential difference between the sensors C and D. The raw data exhibits the sinusoidal variation corresponding to the spin frequency of the rocket with a dc shift which may be due to the slowly changing contact potential of the side sensors. The dc shift was eliminated by taking average of 2 seconds of data set and subtracting it from the corresponding original data set. To remove the spin modulation effect, procedure used in the case of $E_{v'}$ of subtracting a sine wave of identical amplitude as the original data series and phase shifted by $\pi$ degrees was adopted. When the angle between the distance vector, $d$, representing the separation of the side sensors and geomagnetic field lines becomes less than $30^\circ$, then there would be significant disturbance to the sensors due to their interaction with the rocket body and the axial boom via the geomagnetic field lines. Therefore only the values occurring within $\pm15^\circ$ of the peak were used for analysis. To identify the peaks, following method was adopted. The raw data was smoothened by taking 7 point running average, corresponding to 7 ms of data interval (10.5 m assuming rocket velocity to be $\approx 1.5$ km/s) and then gradients were calculated over that period. At the peaks, gradients reverse their sign i.e. switch from positive to negative values or vice versa. The time, $t$, corresponding to the peaks was determined and the $E_{H'}$ values were obtained by taking the average of $t \pm 0.02$ seconds of data to consider the data within an angle of $\pm15^\circ$ with respect to the horizontal. This corresponds to the E-W position of the sensor. As during each spin cycle the polarity of the potential difference measured by the sensors is reversed as the position of the side sensor is interchanged, the absolute values of the peak values were used for the determination of $E_{H'}$. 
5.5 Results

5.5.1 $E_v'$ Measurements

As discussed before, $E_v'$ representing the component of electric field measured along the spin axis is inferred from the potential difference between the sensors A and B. Fig. 5.8 shows the fluctuations in $E_v'$ occurring in various altitude regions. It is observed that around 165 km, structures with half wavelength of about 7 km are present. Smaller scale perturbations superimposed on these large scale structures are also present. Around 175 km, structure with amplitude around 12 mV/m is seen. Structure with amplitude near 5 mV/m and with half wavelength approximately 5 km is observed around 183 km. The amplitude of irregularities observed between 210 - 260 km altitude region is smaller than those seen at the lower altitudes. The maximum amplitude of irregularities in this region is around 4 mV/m. Around 230 km altitude region, structure with half wavelength of about 5 km and amplitude around 4 mV/m is seen. Between 236 km to 239 km, structures with scalesizes varying between 0.5 - 1.5 km and with amplitudes as large as 3.5 mV/m are seen. Around 245 km, perturbations with scalesize around 2.8 km and amplitude around 1.9 mV/m are observed. Fluctuations with scalesize around 2.8 km and amplitude nearly 2.5 mV/m are seen around 247 km. Between 260 - 280 km altitude region, small scale irregularities with amplitude around 1 mV/m are evident. A relatively smooth region is observed between 280 - 290 km. A patch of irregularity in $E_v'$ is seen between 292 - 330 km altitude region. Perturbations with scalesize around 1.4 km are seen between 292 and 295 km with amplitude as large as 2.8 mV/m.

5.5.2 $E_H'$ Measurements

Fig. 5.9 shows the raw data as well as the moving average calculated for different data lengths as discussed in the figure caption, for viewing various scales occurring in $E_H'$ profile with altitude. As the spin rate is...
SHAR (13°42'N, 80°E) OCT. 4, 1988 2130 LT

Fig. 5.8 Electric field fluctuations in the vertical direction.
Fig. 5.9 Variation of horizontal electric field with altitude (a) raw data, (b), (c) and (d) represent the moving average taken for 3, 5, and 7 points for viewing structures with scalesizes > 750 m, 1250 m and 1750 m respectively.
around 3.5 Hz, and since the values around the peak have been considered, the variation of the horizontal electric field \( E_h' \) with altitude is available every 215 km. Hence the vertical structure of \( E_h' \) with \( \lambda > 215 \) m can be studied. It is observed that between 100 - 130 km large perturbations with values as high as 5 mV/m are present. Between 160 - 170 km, a patch of irregularity is seen with values of \( E_h' \) lying between 0.7 - 2 mV/m. High values of \( E_h' \) ranging between 2 - 4 mV/m are seen between 184 - 188 km altitude region. It is to be noted that in this altitude region, \( E_v' \) exhibits a drop from 4 mV/m to -5 mV/m. At around 165 km, irregularities with scalesize around 2.7 km and amplitude around 0.7 mV/m are seen. \( E_h' \) fluctuations with half wavelength nearly equal to 5.5 km and amplitude around 1.4 mV/m are seen at about 172 km. Around 185 km, perturbation in \( E_h' \) values with amplitudes as high as 4 mV/m and scalesize around 3.6 km are observed. Weak fluctuations in \( E_h' \) are evident between 210 - 255 km altitude region, where the maximum value observed is around 0.9 mV/m. Around 215 km, fluctuations in \( E_h' \) having scalesize around 1.8 km and amplitude nearly equal to 0.7 mV/m are observed. At high altitudes i.e. around 292 km, the amplitude of \( E_h' \) fluctuations goes upto 7.7 mV/m and are characterised by scalesize approximately 1 km. Around 332 km, fluctuations in \( E_h' \) of around 4 mV/m are present. Between 295 - 332 km, weak irregularities with values less than 0.6 mV/m are seen.

It is known that the zonal electric field gives rise to the vertical electrodynamic drift given by the expression

\[
V_z = \frac{E \times B}{B^2}
\]

where \( E \) is the zonal field, \( B \) is the earth's magnetic field. As the spin axis of the rocket is inclined by about 8.8° with respect to vertical and the dip angle at SHAR is around 14° N, the vertical electrodynamic drift is given by \( V = E \cos(8.8°)/B\cos(14°) \). Here \( E \) is the electric field measured across the rocket spin axis.
The vertical electrodynamic drift obtained by using the above expression is shown in Fig. 5.10. Since the ac field is measured, the drift is indicative of motion of the irregularities. As mentioned in the previous chapter, at the time of the rocket launch i.e. around 2130 hrs LT, the ionograms recorded at SHAR showed that the F layer was drifting downward indicating that the ambient field was westward. Between 100 - 130 km altitude region, \( V_z \) as high as 130 m/s is observed. Around 185 km, \( V_z \approx 100 \) m/s is seen and high values of \( V_z \approx 250 \) m/s are observed around 292 km. Between 165 to 175 km altitude region, \( V_z \) as high as 50 m/s are seen and in the 210 - 260 km altitude extent \( V_z \) lies between 2 - 20 m/s. The maximum velocity observed between 260 - 280 km region is around 7 m/s. The base of the F layer located around 255 km is seen to drift downward with \( V_z = 19 \) m/s. This matches closely with the velocity calculated using rate of change of \( h'F \) inferred from ionograms which is \( = 20 \) m/s.

Miller et al. (1986) deduced the thermospheric meridional wind from ionospheric \( h_m F_2 \) data. Later on, Krishna Murthy et al. (1990) derived the meridional winds near the magnetic equator directly from \( h'F \) data at two equatorial stations situated nearly on the same magnetic meridian. The vertical drift \( V \) can be written as

\[
V = V_z \cos I - U \cos I \sin I - W_D \sin^2 I
\]  
(5.7)

where \( U \) is the meridional neutral wind in the northward direction, \( W_D \) is the plasma drift due to diffusion, \( V_D \) represents vertical \( E \times B \) drift. Rishbeth et al. (1978) showed that a southward (northward) neutral wind pushes the ionisation up (down) along the field lines. Vertical drift obtained from the ionograms i.e. using \( \Delta h'F/\Delta t \), is the sum of true vertical drift and the apparent vertical drift due to the chemical loss given by \( \beta H \) (Subbarao and Krishna Murthy, 1983), where \( \beta \) is the attachment coefficient and \( H \) is the ionisation scale height. Thus,

\[
V = V_{\text{ion}} - \beta L
\]
(5.8)
Fig. 5.10 Variation of vertical velocity with altitude calculated from the horizontal electric field data.
where $\beta$ has been taken from Anderson and Rusch (1980), $V_{\text{ion}}$ is the velocity inferred from ionograms using $h'F$ data which is around 20 m/s downwards, $L$ is the gradient scale length, $W_D = g/v_n$ (Rishbeth et al., 1978), where neutral parameters for determining $v_n$ have been calculated using MSIS-86 model. At the base of the F layer located around 255 km, $L$ is approximately $3.3 \times 10^2$ m. Thus, the neutral meridional wind at the base of the F layer can be evaluated using the expression:

$$U = \frac{V}{\sin I} - \frac{V}{\cos I \sin I} - W_D \tan I \quad (5.9)$$

Substituting the values of $V_z$, $V$, and $W_D$, observed at the base of the F layer, the meridional wind at the base of the F layer is estimated to be 78 m/s in the northward direction.

### 5.5.3 Correlation Study between Electron Density and Electric Field Irregularities

As mentioned in Chapter 4, electron density irregularities were observed in three different patches occurring between 165 - 175 km, 210 - 255 km and 290 - 330 km altitude regions. It is observed that the fluctuations in $E_{\nu}'$ and $E_{H}'$ are colocated with the electron density irregularities as seen in Fig. 5.11. One of the remarkable features during this flight is the simultaneous occurrence of irregularities below the base of the F-region, at the base, and as well as above the base. This provided a unique opportunity for studying the nature of electron density and electric field irregularities at different altitude region simultaneously. This was done by performing the correlation studies between $n_e$ and $E_{\nu}'$ and $n_e$ and $E_{H}'$ for every 10 km of data sets. This study showed that the large scale irregularities in $n_e$ and $E_{\nu}'$ seen below the base of the F region i.e. around 160 - 175 km, exhibit strong anti-correlation. However fluctuations in $n_e$ and $E_{H}'$ display poor anti-correlation. Around 165 km, the correlation coefficient between $\delta n_e$ and $\delta E_{\nu}'$ is around -0.76 while that between $\delta n_e$ and $\delta E_{H}'$ is about -0.2. Similarly, around 175 km, fluctuations in $\delta n_e$ and $\delta E_{\nu}'$ display
Fig. 5.11 Horizontal electric field, electron density and vertical electric field perturbations during the ascent of the rocket showing the simultaneous occurrence of irregularities.
correlation coefficient equal to -0.83 and that between $\delta n_e$ and $\delta E_{H'}$ is nearly -0.54 as shown in Fig. 5.12.

A very interesting feature is observed in 210 - 255 km altitude range. The relationship between electric field and electron density irregularities observed in this region show a different trend. In this region electron density fluctuations are strongly correlated with $\delta E_{V'}$ while with $\delta E_{H'}$ they display poor correlation. Very strong correlation is seen between $\delta n_e$ and $\delta E_{V'}$ around 245 km with correlation coefficient $\approx 0.9$. An example can be seen in Fig. 5.13. This trend of correlation changes to anti-correlation at higher altitudes i.e. for irregularities occurring above the base of the F layer. Around 305 km, a high correlation coefficient with value $\approx 0.92$ is observed for $\delta n_e$ and $\delta E_{V'}$. But the fluctuation in $E_{H'}$ display poor anti-correlation. The variation of correlation coefficient between the electric field and electron density calculated for every 10 km of data sets along with the percentage amplitude of irregularities in the intermediate scales is shown in Fig. 5.14. Hysell et al. (1994) observed irregularities in $n_e$ and electric field simultaneously and found that $\delta E_{H'} \approx -\delta n$ on large scales. They also observed that the large scale features in vertical electric field are also anti-correlated with $\delta n$ although not so clearly as observed in the $E_{H'}$. This observation is in contrast to our measurements. The observation of strong correlation seen around the base of the F layer, where the large amplitude irregularities occur, is very interesting. Charge neutrality condition imposes the restriction that the current in the F region be divergence free. As the F region currents lie principally in the x direction, $J_x$ must be nearly continuous. When the density and Pederson conductivity are non-uniform, polarisation charges accumulate at horizontal density gradients giving rise to horizontal electric field in such a way that $\nabla \cdot J = 0$. Thus $E_{H'} \approx -\delta n$. Hysell et al. (1994) attributed the anti-correlation between $\delta E_{V}$ and $\delta n$ to the eastward neutral wind which drives the current in the vertical direction and produces vertical polarisation field which might be responsible for the production of plasma irregularities (Tsunoda et al., 1982).
Fig. 5.12 Electron density and electric field fluctuations in 170-180 km altitude region displaying anti-correlation between them.
Fig. 5.13 Figure showing the correlation between electric field and electron density fluctuations.
Fig. 5.14 Variation of (a) correlation coefficient, $r$, with altitude between electric field and electron density computed every 10 km and (b) the % amplitude of electron density fluctuations in 0.2 - 8 km scalesize range with altitude.
Fig. 5.15 Variation of electron density, $E'_v$ and $E'_h$ with altitude showing the presence of high frequency components in the vertical electric field fluctuations only.
Fig. 5.16 Variation of fluctuations in electron density, vertical electric field and horizontal electric field with altitude. This figure shows that magnitude of high frequency component increases in the region where strong electron density irregularities occur.
Fig. 5.17 Example of saw-tooth structures in electron density and horizontal electric field profile in lower altitude region.
Fig. 5.18 Example of saw-tooth structures at higher altitude of opposite character than those observed at lower altitude as shown in Fig. 5.17.
5.5.4 Power Spectral Analysis of Irregularities

It is known that the relationship between electron density irregularities and electric field fluctuations serves as an important clue to the plasma instabilities and processes acting during spread F as has been discussed in Chapter 1.

To study the spectral nature of irregularities in $E_H'$ and $E_V'$, a composite spectra of scalesizes ranging from very large to about one meter was obtained. This was accomplished by making use of dc (0 - 100 Hz) channel data and mid frequency (MF) channel data having frequency response between 50 - 500 Hz. As the amplitude of the small scale irregularities is small, additional gains of 75 and 25 were used to amplify the amplitude of these smaller scale structures. Visual inspection of the data was performed for selecting the times of low gain and high gain periods. Since the amplitude saturated during most of the high gain period, data sets corresponding to low gain period were considered for spectral analysis. For obtaining the composite spectra, MF channel data was normalised with respect to the DC channel data at 60 Hz. The normalisation was performed by taking 7 point running average of DC channel data and then fitting a least square best fit line to the data set. Similarly, MF data was smoothened by taking 5 point moving average and then the power obtained at 60 Hz from MF data was normalised to that obtained by DC channel data. Power spectra of the irregularities was obtained for 2 seconds of data set of DC channel and the corresponding MF channel data.

The composite spectra $E_V'$ and $E_H'$ thus obtained are shown in Fig. 5.19 and 5.20 for a few selected altitude regions. From these spectra the spectral indices have been calculated for intermediate, transitional and short scalesize ranges and the same are tabulated below.
Fig. 5.19 Power spectra of vertical electric field fluctuations at 221 km, 235 km, 301 km, 312 km and 320 km.
Fig. 5.20 Power spectra of electric field fluctuations across the spin axis
234 km, 247 km, 263 km, 291 km, 293 km and 324 km.
Table 5.1 Spectra of $\delta E_{h'}$ fluctuations.

<table>
<thead>
<tr>
<th>Altitude km</th>
<th>$\lambda$ (100 m-1 km)</th>
<th>$\lambda$ (10-100 m)</th>
<th>$\lambda$ (&lt; 10 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>210-255</td>
<td>-1.2 ± 0.5</td>
<td>-3.0 ± 0.9</td>
<td>-1.8 ± 0.8</td>
</tr>
<tr>
<td>290-330</td>
<td>-1.2 ± 0.5</td>
<td>-2.5 ± 1.4</td>
<td>-2.5 ± 1.4</td>
</tr>
</tbody>
</table>

Table 5.2 Spectra of $\delta E_{v'}$ fluctuations

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>$\lambda$ (100 m-1 km)</th>
<th>$\lambda$ (10 m-100 m)</th>
<th>$\lambda$ (&lt; 10 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>210 - 255</td>
<td>-1.2 ± 0.7</td>
<td>-3 ± 0.9</td>
<td>-2.5 ± 1.4</td>
</tr>
<tr>
<td>290 - 330</td>
<td>-1.2 ± 0.8</td>
<td>-2.5 ± 1.4</td>
<td>-1.6 ± 1.4</td>
</tr>
</tbody>
</table>

It is observed that the irregularities in $E_{v'}$ and $E_{h'}$ occurring in the intermediate scales ($\lambda \sim 100$ m - 1 km) display shallow spectral indices both in the lower (210 - 255 km) and higher altitude (290 - 330 km) region. The spectral index for $E_{v'}$ fluctuations is ~ -1.2 ± 0.8 while for $E_{h'}$, it is around -1.2 ± 0.5. It has been mentioned earlier in Chapter 4 that electron density irregularities exhibit shallow spectral indices for intermediate scales ranging between -1 and -2. This supports the contention that the irregularities in the intermediate scales are generated through GRTI mechanism.

The irregularities in the transitional scales ($\lambda \sim 10$ m - 100 m) display spectra with spectral indices around -3 ± 0.9 for both $E_{v'}$ and $E_{h'}$ in 210 - 255 km altitude region. However, the electron density irregularities in the transitional scales, in this region display steeper spectrum with spectral index ranging between -2.5 and -5. In the higher altitude region (290 - 330 km), the electric field spectrum display spectral index around -2.5 ± 1.4 and electron density display spectral indices in the range -2.5 and -4.5.

Irregularities in $E_{v'}$ occurring in 165 - 175 km altitude region exhibit steep spectra. Around 165 km, fluctuations with $\lambda \sim 40$ m - 1 km can be
represented by a single power spectral index nearly equal to -4.09. There is an indication of a break in spectrum near 40 m, i.e., for scalesize < 40 m, spectrum becomes shallower. Around 169 km, electric field irregularities with $\lambda > 11$ m display spectra with spectral index ~ 3.6 and for short wavelength, the nature of the spectrum changes. Irregularities occurring near 172 km with $\lambda > 32$ m follow power law with spectral index ~ 3.28. For smaller scales it becomes shallower. Around 176 km, strong irregularities are seen which display spectral index around -3.3. A break in spectrum is observed around $\lambda \sim 9$ m where it becomes shallower. It is interesting to note that $E_{\nu'}$ and electron density spectra display nearly the same spectra. This is probably the manifestation of the fact that electron density and vertical electric field irregularities display either strong correlation or anti-correlation as discussed in Section 5.5.3.

The nature of the spectra observed around the base of the F layer is markedly different from the spectra observed at the higher altitudes. Around 256 km, the spectra of $E_{\nu'}$ steepens near $\lambda \sim 75$ m and there is an indication of the spectrum becoming shallower for $\lambda < 36$ m. At about 221 km, spectra becomes steep near $\lambda \sim 33$ m and around 15 m it changes to a shallower spectra. Thus the nature of the spectra is highly variable and may be partly due to the temporal variations of irregularities. In the region 260 - 280 km, where the amplitude of irregularities is weak, the spectrum merges with the noise level determined by telemetry for $\lambda < 13$ m. At higher altitudes, around 309 km spectrum display shallow behaviour for $\lambda > 104$ m and becomes steeper between 10 and 104 m. For $\lambda < 10$ m, there is an indication of the spectrum becoming shallower.

5.6 Discussion

It was observed that the irregularities in electric field and electron density displayed the anti-correlation between 165 - 175 km and 290 - 320 km altitude regions. This is expected due to generation of polariisation electric fields which develop to maintain divergence free conditions as
discussed earlier. However, a very interesting phenomenon is observed between 210 - 255 km altitude region where electric field and electron density display strong correlation. This can be understood by considering the motion of charged particles in the directions perpendicular to B, which can be expressed, using the equations for conservation of momentum (Kelley, 1989) as given below.

\[ 0 = -k_B T_j (\partial n / \partial x) + n q_j E_x + n q_j V_{jy} B - n M_j v_{jn} V_{ix} \]  
\[ 0 = -k_B T_j (\partial n / \partial y) + n q_j E_y + n q_j V_{jx} B - n M_j v_{jn} V_{iy} \]  

(5.10)  
(5.11)

where \( M_j \) refers to the mass of the ion species, \( V_{ix,y} \) is the velocity of the plasma constituents, B is in the z direction. From the above equations, \( V_{ix} \) and \( V_{iy} \) can be written as:

\[ V_{ix} = \left( 1 + \frac{q_j^2 B^2}{M_j^2 v_{jn}^2} \right) \frac{-k_B T_j}{M_j v_{jn}} \frac{1}{n} \partial n \]  
\[ V_{iy} = \left( 1 + \frac{q_j^2 B^2}{M_j^2 v_{jn}^2} \right) \frac{-k_B T_j}{M_j v_{jn}} \frac{1}{n} \partial n \]  

(5.12)

Since, the \( E \times B \) drift and the diamagnetic drift velocities can be written as

\[ V_{Ei} = \frac{E \times B}{B^2}, \quad V_{Di} = \frac{k_B T_j}{q_j B^2 n} \n \times B \]  

(5.12)

The equation for the perpendicular velocity can be combined and written as

\[ V_{\perp} = \left( 1 + \frac{q_j^2 B^2}{M_j^2 v_{jn}^2} \right) \frac{-k_B T_j}{M_j v_{jn}} \n \times B \]  
\[ - \frac{k_B T_j}{M_j v_{jn}} \n \times B \]  
\[ - \frac{q_j B^2}{M_j^2 v_{jn}^2} \n \times B \]  

(5.12)

Defining the perpendicular diffusion coefficient for the motion antiparallel to a density gradient by an expression of the form \( V = -D (\n \times n) \),

\[ D_{\perp} = \frac{k_B T_j}{M_j v_{jn}} \left( 1 + \frac{\Omega^2}{v_{jn}^2} \right) \]  

(5.13)
In the F region, gyrofrequencies are much greater than the collision frequencies, therefore the above expression is reduced to:

$$D_{\perp} = \frac{k_B T_i}{M_i} \left( \frac{v_{in}}{\Omega_{in}} \right)$$  \hspace{1cm} (5.14)

The perpendicular diffusion coefficient of species j can be written as

$$D_{\perp j} = r_j^2 v_j$$ \hspace{1cm} (5.15)

where, $v_j$ represents the collision frequency, $r_j$ is the gyroradius which is expressed as

$$r_j^2 = \left( \frac{k_B T_i}{M_i} \right)^{1/2} \Omega_j^{-1}$$ \hspace{1cm} (5.16)

Since $r_j$ is much larger for ions than for electrons, the ions tend to diffuse more rapidly down a density gradient which exists perpendicular to the magnetic field than the electrons. When this occurs an electric field builds up parallel to $\nabla n$, so the ion motion across the field lines is retarded and the electron motion is enhanced. This may be the reason for the positive correlation seen in the altitude range of 210 - 260 km in the present flight. Such process results in the diffusion of plasma structure across a magnetic field with a diffusion coefficient equal to the low electron diffusion coefficient. Kelley et al. (1982a) calculated the relative amplitude of kilometre scale structures produced at various places in auroral oval which were then allowed to convect through regions of varying E-region conductivity. Vickrey and Kelley (1982) showed that the cross field diffusion at high latitudes results in the formation of images in the E region which tend to slow diffusion process. They discussed that the image will reduce the decay of F region structure by limiting the field aligned current that would otherwise reduce the ambipolar electric field. Since it is this field which impedes ion diffusion, the formation of E region reduces the F region cross field diffusion rate. Later on, Vickrey et al. (1984) explained the
formation of irregularities below the bottomside of the F region at low latitudes on the basis of the image mechanism.

The electric field experiment carried abroad the San Macro D equatorial ionospheric satellite revealed the downdrafting motion inside depletion regions (Laakso et al., 1994). McClure et al. (1977) and Hanson and Bamgboye (1984) also reported downdrafting motion of the ionisation irregularities. Laakso et al. (1994) pointed out that both updrafting and downdrafting motions are expected on the basis of generalised gradient drift or collisional R-T instability process in the ionospheric F-region. It is known that the gravitation would result in upward plasma flow in plasma depletion regions. However, both background westward zonal electric fields and upward vertical neutral winds can cause an occurrence of downdrafting if those parameters are strong enough. They showed that as the background zonal electric field becomes westward (after ~ 2100 LT) in the equatorial ionosphere, the plasma inside the bubbles at altitude ~ 400 km and less at magnetic equator may assume a downdrafting motion (~ 100 m/s), while at higher altitudes in the same flux tube, the plasma flow remains upward. Such simultaneous occurrence of the updrafting and downdrafting plasma flow in a single bubble channel may lead to the pinching off the upper part of the depletion region from the lower altitude regions, causing the decay of a bubble or the formation of a dead bubble. Aggson et al. (1992) reported such pinched off bubbles (dead bubbles) using double probe experiment carried on board San Macro D satellite. They suggested that after approximately 15 min the type I events (live bubbles) may be pinched off from the low densities of the bottomside F region and the bubbles probably become type II events (dead bubble) which continue to drift eastward with the general background zonal plasma flow.

Laakso et al. (1994) showed that the electric field inside the bubble ($E_{yi})$ can be expressed by the following relation,
where the subscript 0 refers to values outside of the bubble \((E_{y0}, n_0)\) and the subscript 1 refers to values inside the bubble \((E_{y1}, n_1)\), \(U_x\) is the zonal neutral wind. This equation indicates that the downdrafting plasma flow can occur if the background electric field is oriented westward and the gravitational term minus the neutral wind speed term is small. They observed a number of depletion regions with downdrafting velocity at altitudes below 350 km in the F region near to geomagnetic equator. They found that these bubbles were characterised by enhanced westward electric fields of several millivolts per meter corresponding to downward flow speeds of about 50 - 150 ms\(^{-1}\). The altitude of the transition between the updrafting and downdrafting flows at the magnetic equator as a function of background zonal electric field suggested by Laakso et al. (1994). They suggested that below 350 km, the downdrafting velocities can occur if the ambient \(E_y\) is more negative than -0.4 mV/m. It was seen from the ionograms obtained from SHAR that the F layer was descending indicating that the ambient field is westward \((E_h' - 0.8 \text{ mV/m})\) during the rocket flight pertaining to the present study. Around 292 km vertical drifts as high as 250 ms\(^{-1}\) have been observed.

Our data indicated the presence of spikes in \(E_{y'}\) only. This observation is consistent with those of Hysell et al. (1994). They surmised that the spikes in the \(E_y\) profile are indicative of an ambipolar electric field. As ions attempt to diffuse across steep vertical gradients, an ambipolar electric field arises to inhibit their transport and bind them to the more tightly bound electrons. Thus charge neutrality is maintained. The electric field spike is more if the density gradient is steep. This field is given by \(\delta E - \rho^2 \Omega_i B/L\) where \(\rho\) is the ion Larmor radius, \(\Omega_i\) is the ion cyclotron frequency, and \(L\) is the gradient scale length. The relative absence of intense spikes in the zonal direction suggests that the most abrupt gradients in the plasma are in the vertical direction.